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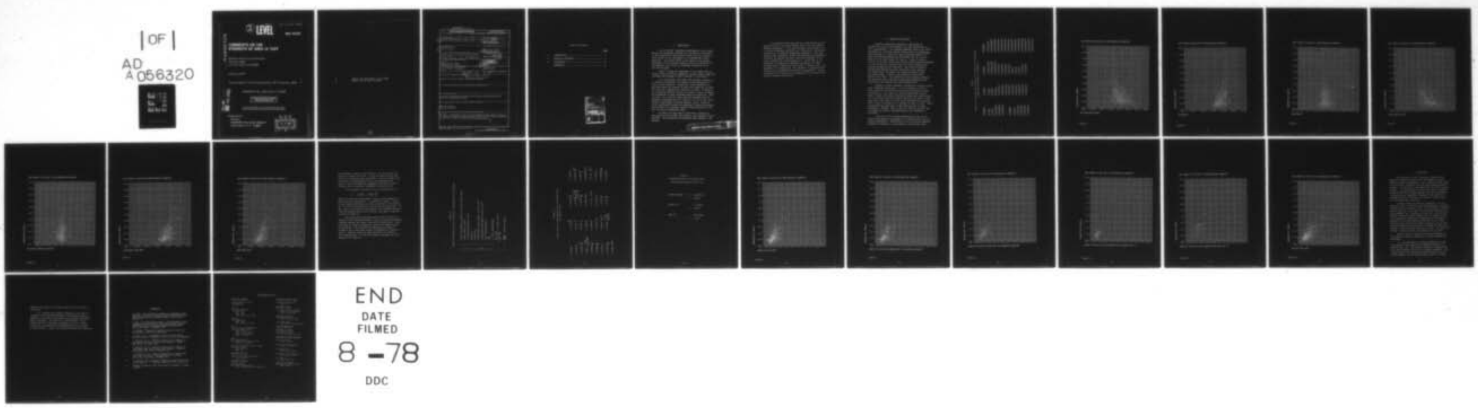

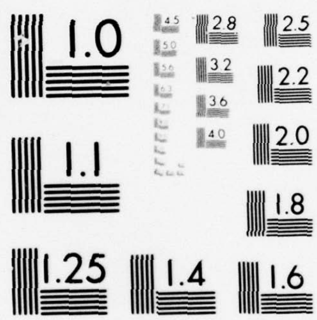
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COMMENTS ON THE STRENGTH OF AREA 12 TUFF

Systems, Science and Software
P.O. Box 1620
La Jolla, California 92038

February 1978

Topical Report for Period November 1977—February 1978

CONTRACT No. DNA 001-77-C-0099

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Material Strength
Material Properties

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An effort is described to find a relation between measured stress difference at 4 Kbar as determined by uniaxial strain tests and other material properties for NTS area 12 tuff. No useful relationship was found.

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Table of Contents

1. INTRODUCTION

One of the most interesting developments in the recent history of containment research has involved the realization of the importance of the residual stress field as a significant feature of the containment of an underground nuclear explosion. This stress field is the result of the plastic deformation of the geologic material during the formation of the explosive cavity and its subsequent relaxation to an equilibrium state.

Rimer[1] showed the dependence of the stress field on several relevant material parameters, and his results have been confirmed and extended by App,[2] Terhune,[3] and Allen.[4]

All investigators have shown that material strength is an important determinant of residual stress magnitude for a given initial condition. Relatively little information is available about the strength of geological materials of interest, and such information is difficult to obtain. Therefore, an interesting question involves the extent to which strengths are determined by other measurable material properties. Specifically, if it could be shown that the strengths could be estimated reasonably well as a function of, let us say, water content, sound speed, and grain density, such a relation could significantly extend our knowledge of material strengths and our ability to estimate residual stress magnitude at the site of future contemplated tests.

An effort has been made to seek such a relation by what might best be called a brute-force, least-squares fitting approach. No preconceived relationships were assumed in the process.

The numerical work was done by a least-square fitting program written at the UCLA medical school entitled "BMD02R, Stepwise Regression." This code generates least-squares fits of a set of dependent variables as a function of a practically unlimited set of possible independent parameters. The code examines the correlation between the dependent and independent variables and chooses the most significant parameter to be used in generating a least-squares fit. After that fit is performed, the remaining independent parameters are again examined and the second most significant is chosen, and a two-parameter fit is generated. This sequence is continued until further fitting becomes statistically insignificant. During the course of a fitting cycle, parameters can be either introduced or removed from the fit.

2. TECHNICAL DISCUSSION

Material properties information, determined by TerraTek for area 12 tuff samples, was used exclusively in this investigation. The strength parameter used is the stress difference at 4 Kb from uniaxial strain tests as scaled from data published in a series of recent TerraTek reports.[5-9] These strength parameters were determined for the 48 drill holes in E, N and T tunnels of area 12, listed in Table I. A total of 471 data points were found in which stress difference at 4 Kb as well as a complete suite of other material properties information was available. The other information included as-received and grain densities, water contents, and longitudinal and shear-sound speeds determined from ultrasonic tests. Porosity and saturation values were derived from these. For purposes of this exercise, porosity and saturation were treated as independent parameters even though they were derived from other measurements.

Figures 1-7 show "strength" plotted as a function of the seven "measured" quantities. It is interesting to note in every case that the relations can best be described as shotgun patterns. In no case is a clear relationship evident. Figure 1 shows the relation between strength and water content. It is quite true that the field of data can be limited on the upper right hand side by a line which indicates that strength goes to zero at roughly 32 wt. percent of water in tuff. Such a relationship has been used in some calculations of event parameters. However, that is only one limit to the data and can hardly be called a representation of the information available.

This set of 471 strength determinations was fit by linear least-squares techniques to an optimum choice from 113 possible parameters. Specifically, the fit used the measured parameters themselves, various modulii derived from them,

Table I

Sources for 471 Data Points Used in a Study of the Influence of Material Properties on Strength

E Tunnel	N Tunnel	N Tunnel	N Tunnel
UE12E#1	UE12N#8	U12N09U69SA#1	U12N101SS#1
UE12E#3	UE12N#9	U12N09UG9SA#2	U12N10ADNRE#1
U12E14UG#3	UE12N#10	U12N09UG9Misc	U12N10ADNHF#3
U12E14UG#10	U12N05UG#4	U12N10UG#1	U12N10AGSCH#1
U12E18GZ#1	U12N05UG#8	U12N10UG#2	U12N10AGSCH#2
	U12N07UG#10	U12N10UG#5	U12N10AGSCH#3
T Tunnel	U12N07UG#11	U12N10UG#7	U12N10AGSCH#4
	U12N07UG#12	U12N10A	U12N10AGSHF#3
U312T#3	U12N08UG#9	U12N10B	U12N10AGSHF#4
U12T01UG#1	U12N08UG#9a	U12N10C	U12N10AGSHF#6
U12T03UG#2	U12N08UG#10	U12N10HF#2	U12N10AGSHF#8
U12T03UG#3	U12N08UG#11	U12N10HF#4	U12N10AGSHF#9
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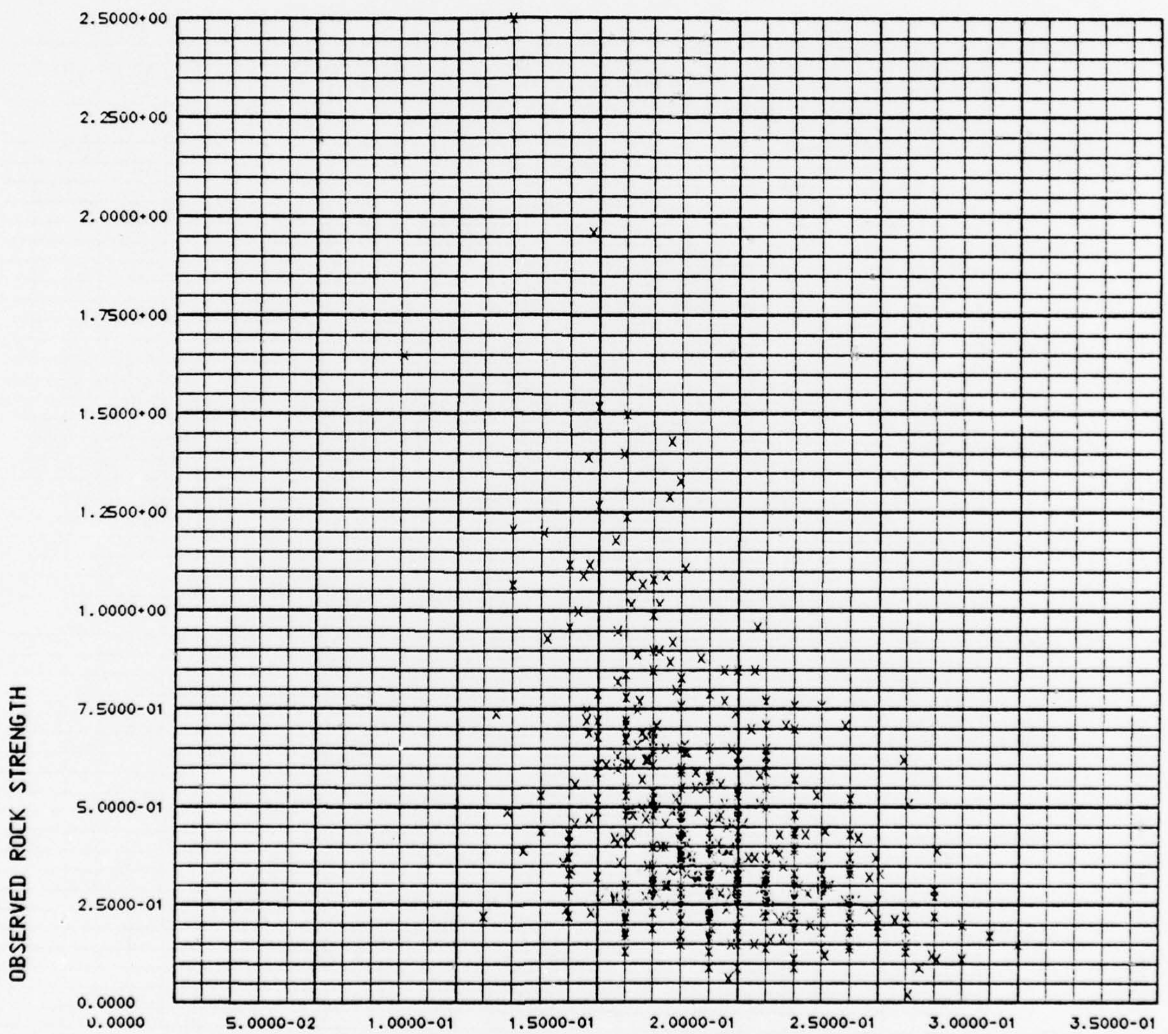
			U12N10ALLCI#1

ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES



MASS FRACTION OF WATER

Figure 1.

ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES

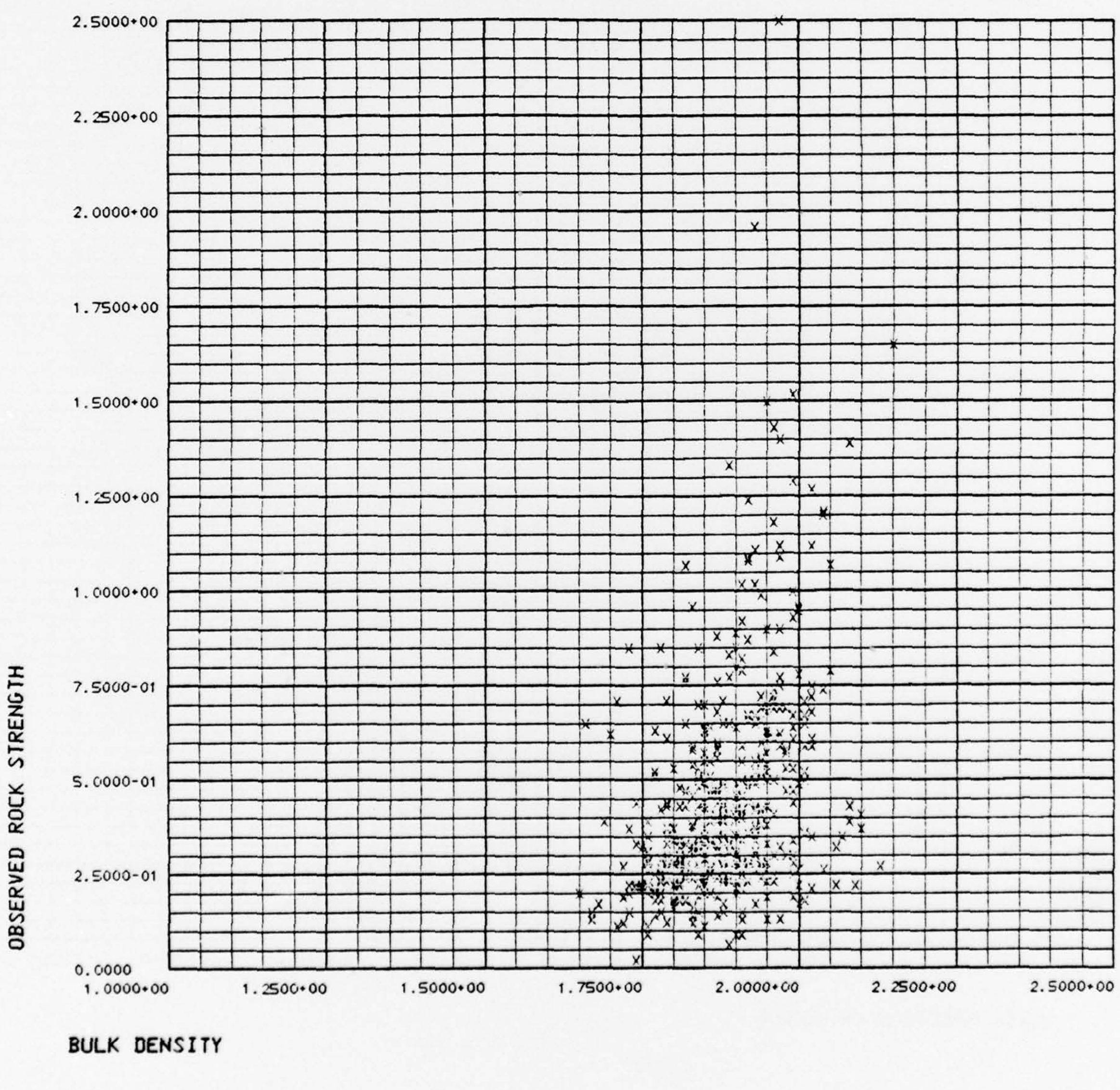


Figure 2.

ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES

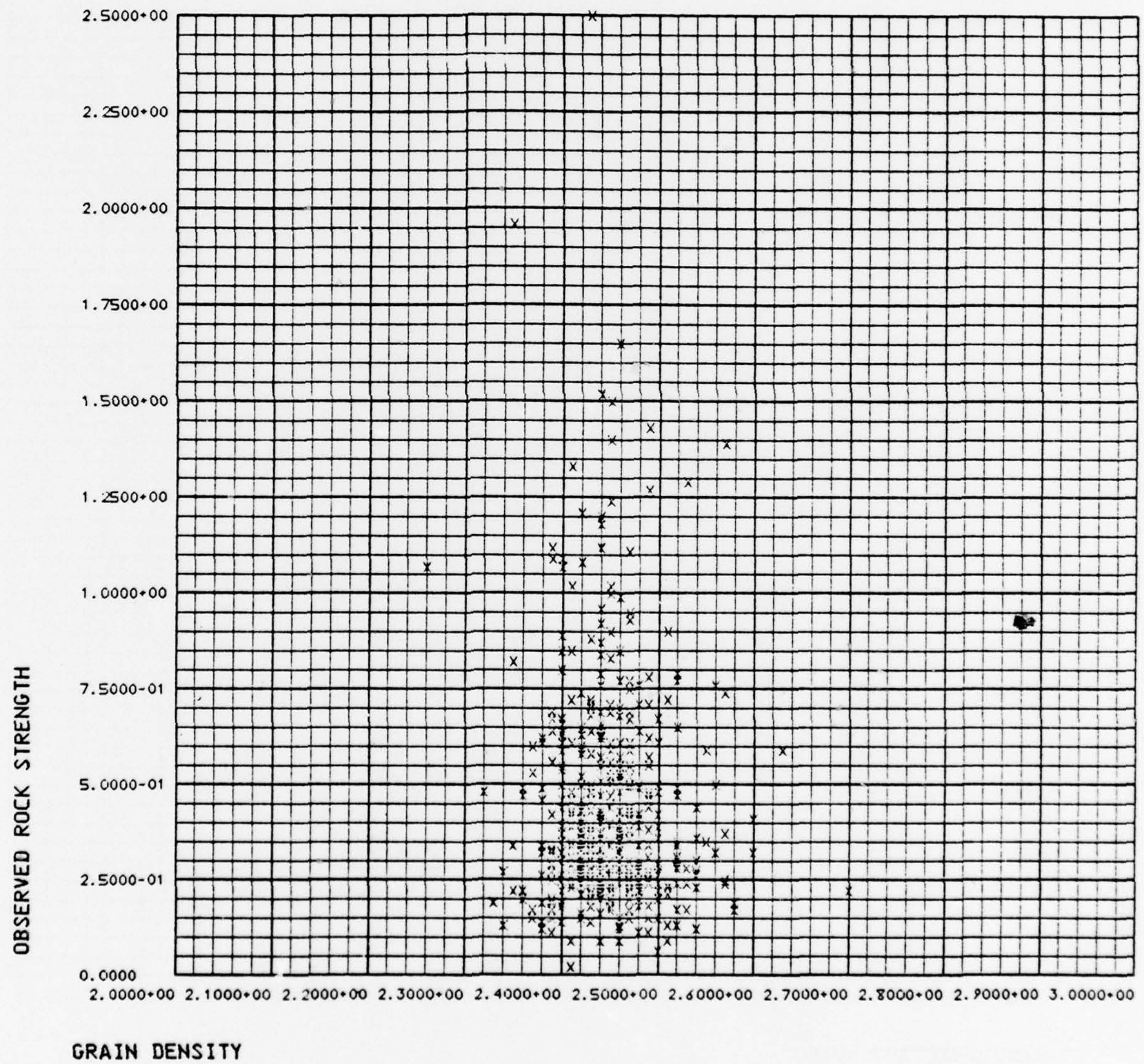


Figure 3.

ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES

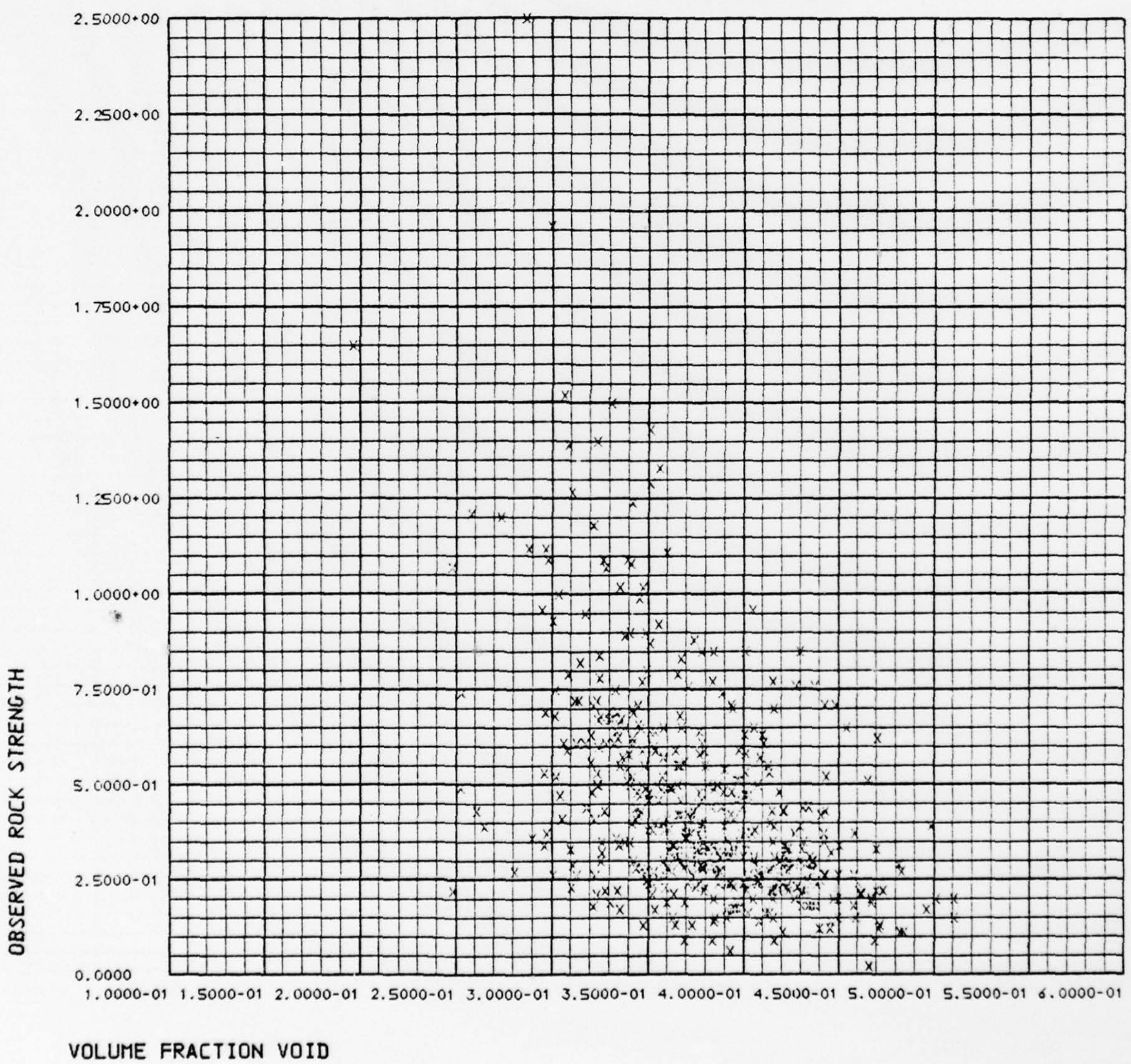
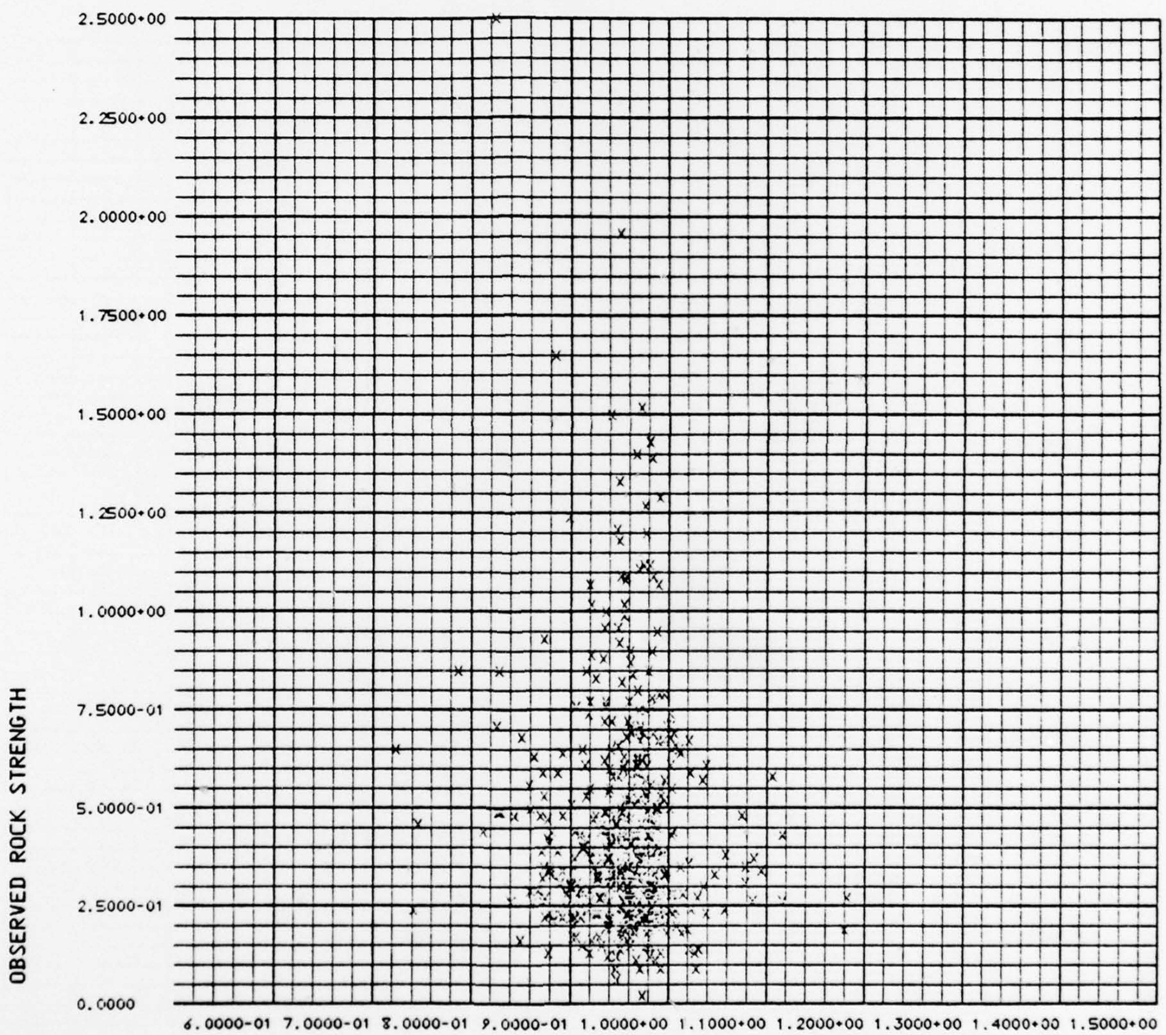


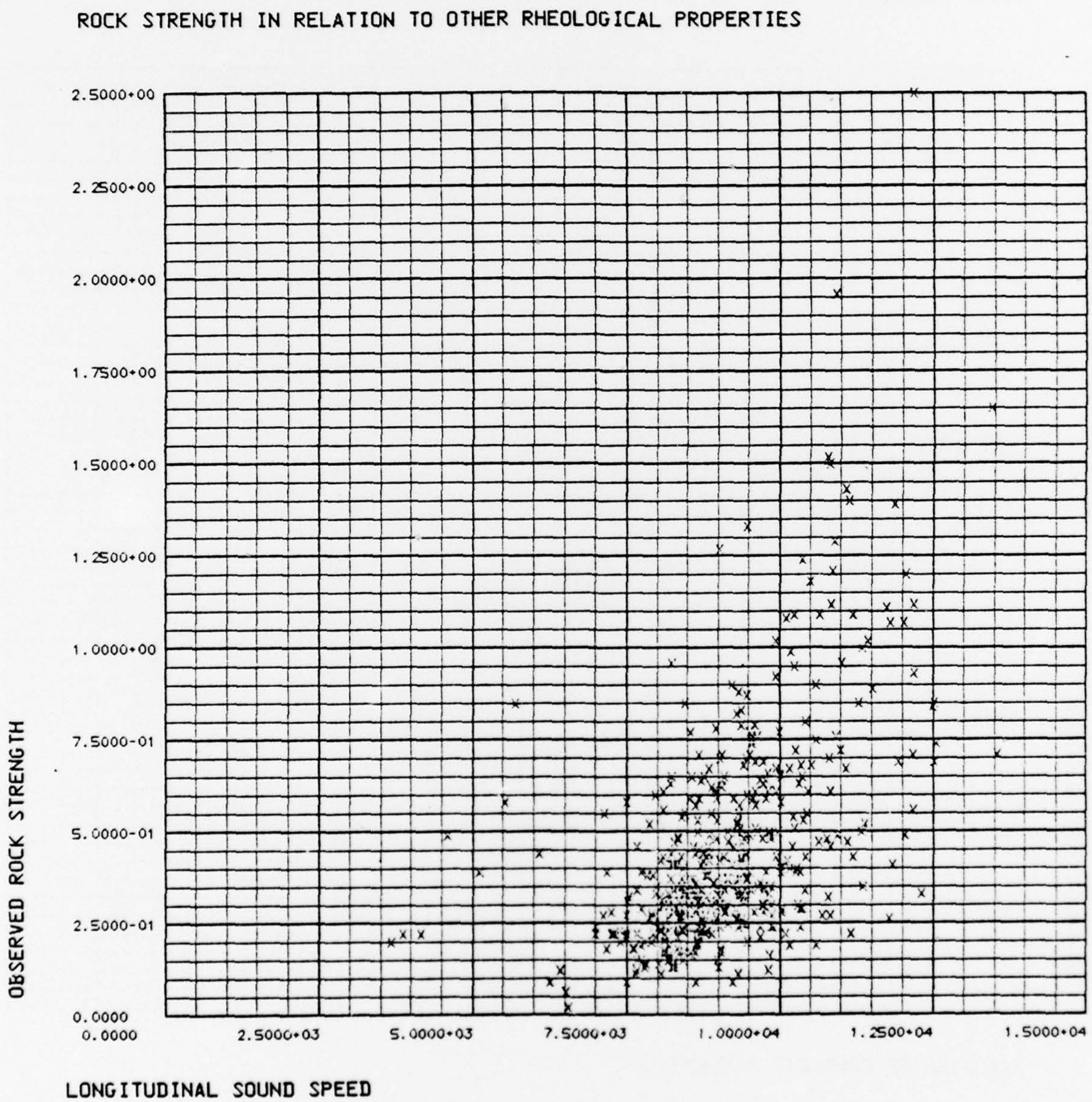
Figure 4.

ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES



FRACTION OF COMPLETE SATURATION

Figure 5.


ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES
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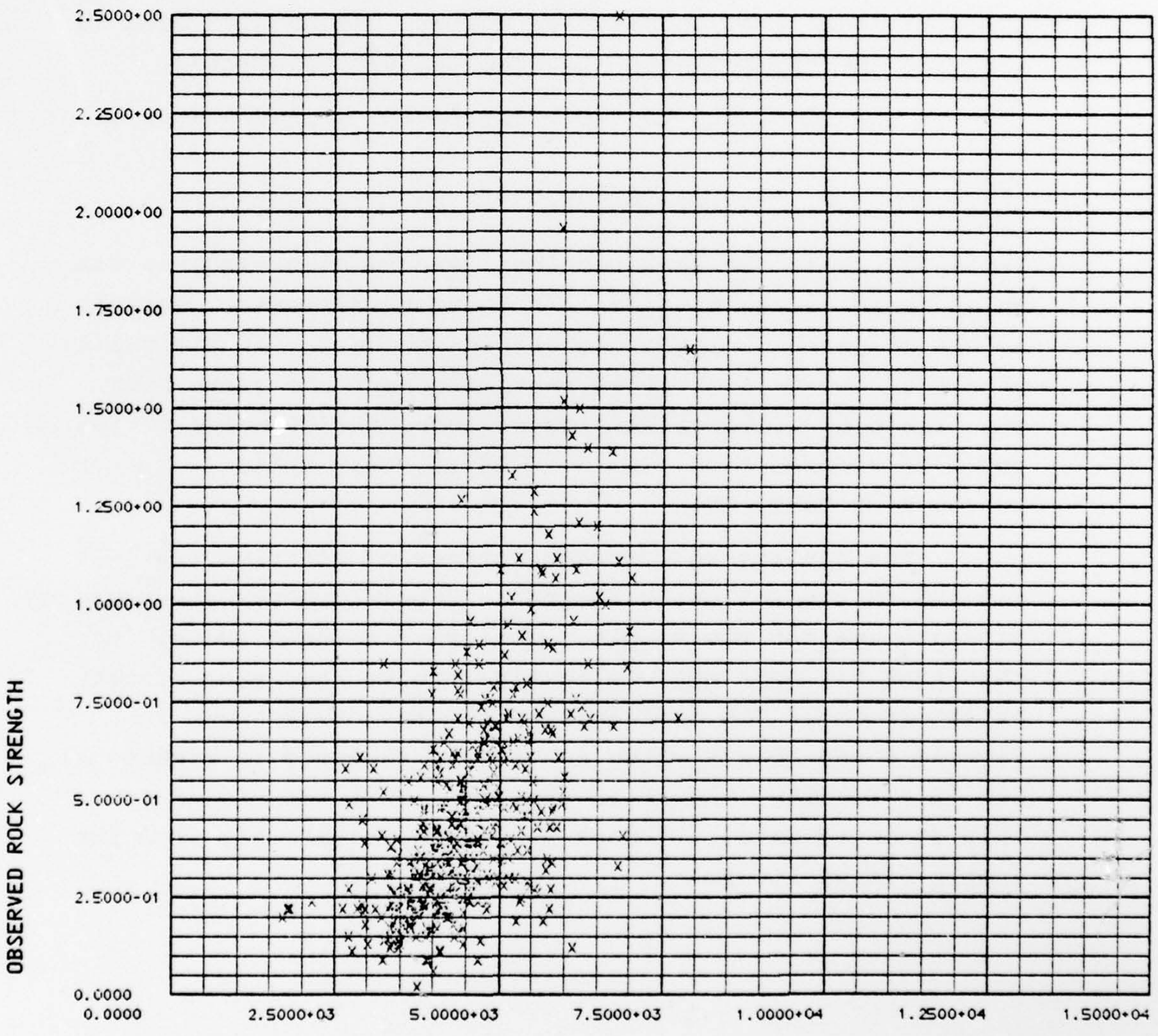
1.5000+00
1.2500+00
1.0000+00
7.5000-01
5.0000-01
2.5000-01
0.0000
0.0000
2.5000+03
5.0000+03
7.5000+03
1.0000+04
1.2500+04
1.5000+04
OBSERVED ROCK STRENGTH
LONGITUDINAL SOUND SPEED

Figure 6.

ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES



SHEAR SOUND SPEED

Figure 7.

miscellaneous ratios of these modulii, and the squares and inverses of these variables. It must be admitted that some pretty wild functions were generated, as will be evident from the actual fit developed which will be presented below. Table II lists the important parameters and modulii used to generate the 113 potential independent variables used.

The simplest, two-term fit to the strength data is:

$$S = 0.08278 + 0.64020 \frac{V_s^2}{\phi}$$

Table III shows the most complex, linear, least-squares fit which could be constructed. It contains 33 terms. Insofar as the standard deviation is a good indication of the quality of a fit, the fits obtained in this effort are quite poor. At the limit of statistical significance, the standard deviation could be reduced from 0.29 to 0.20 Kb, only about 30 percent as shown in Table IV.

The quality and characteristics of the fits are indicated in the following figures. Figure 8 plots the measured strength against the simple, two-term fit shown above. Note that that fit does not explicitly involve the water content or saturation. The influence of saturation is shown in Figures 9 and 10 and water content is examined in Figures 11 and 12. Finally, Figure 13 shows the best fit found to this strength data. It does not differ noticeably from the simple fit of Figure 8.

Table II

Table of Variables Used to Construct Independent Fit Parameters

S	=	stress difference at 4Kb in uniaxial strain, kbar
ρ_G	=	grain density, mg/m^3
ρ	=	as received density, mg/m^3
ϕ	=	porosity
F	=	saturation
V_L	=	longitudinal sound speed, ft/sec x 10^{-4}
V_S	=	transverse sound speed, ft/sec x 10^{-4}
G	=	$\rho V_S{}^2$, shear modulus
L	=	ρV_L^2
K	=	$L - \frac{4}{3} G$, Bulk modulus
σ	=	$\frac{V_L^2 - 2V_S^2}{2(V_L^2 - V_S^2)}$, Poisson's Ratio
E	=	$\frac{9\ GK}{G+3K}$, Young's modulus

Table III

"Best" Linear, Least-Squares Fit of Strength Data
for Area 12 Tuff

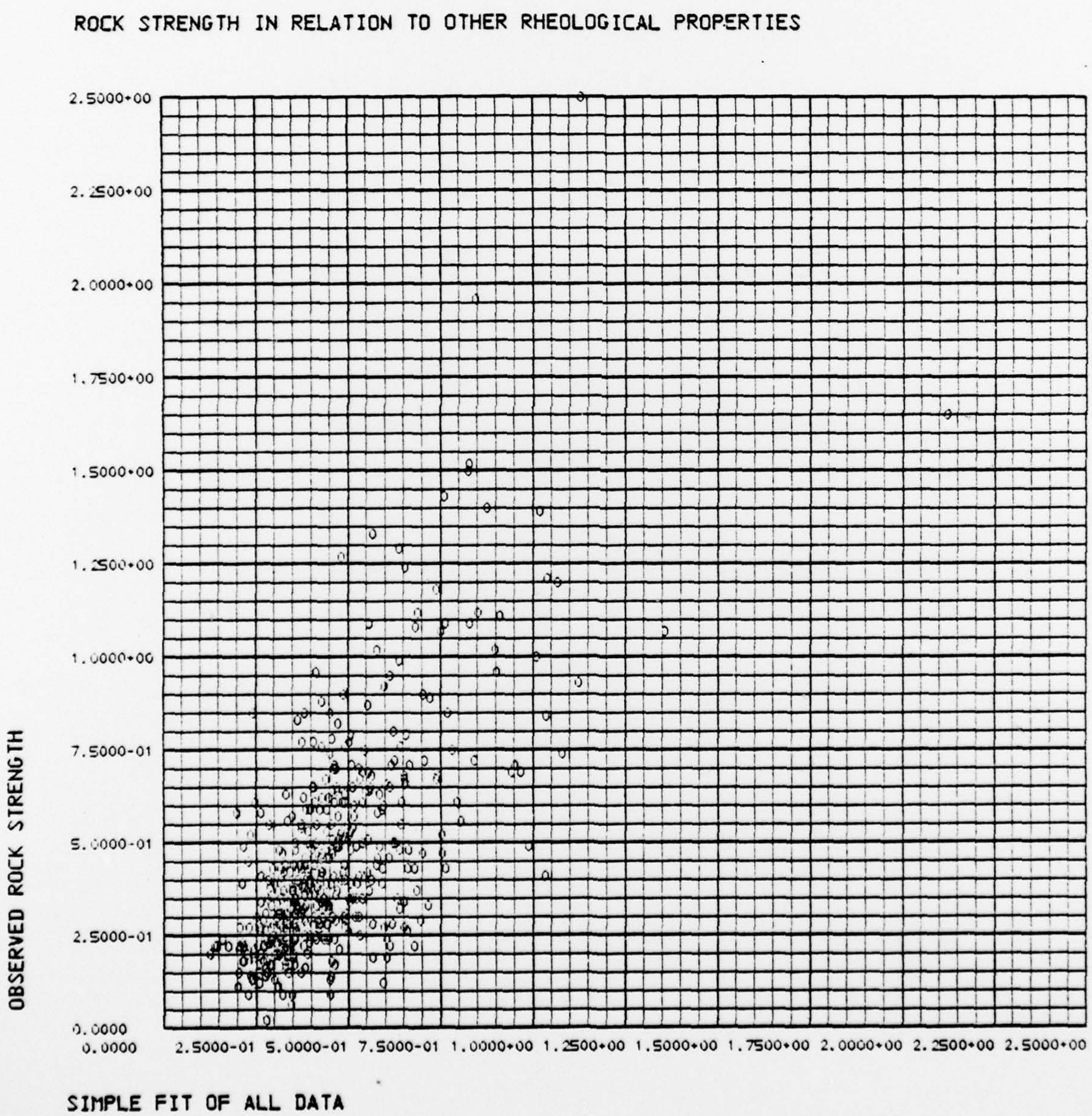
$$
\begin{aligned}
S = &- 18.7831 &&+ 2.7240 \frac{V_S^2}{\phi} &&+ 0.08121 \frac{K^2}{\phi} &&- 1.4970\, KL \\
&+ 33.260 \frac{1}{\rho} &&- 18.542\, L\phi &&- 10.280 \left(\frac{G^2}{L^2-G^2}\right)^2 &&+ 0.07688 \left(\frac{G}{H}\right)^2 \\
&- 0.11905 \left(\frac{L}{\phi}\right)^2 &&- 26.865\, V_S &&- 0.25480 \frac{1}{H\phi} &&+ 1.9262 \frac{H}{G} \\
&+ 7.6831 \frac{\rho_G G}{\rho(1-\phi)^{2/3}} &&+ 2.1037 \frac{L}{\phi} &&+ 8.9504 (K\phi)^2 &&+ 0.07808 (KL)^2 \\
&- 0.23785 \frac{1}{KH} &&+ 0.9499\, F^2 &&- 37.326 (\phi - H\rho) &&- 36.153 \left(\frac{H}{\phi}\right)^2 \\
&+ 0.57805 \frac{1}{K\phi} &&+ 0.79272\, \rho_G^2 &&+ 0.05004 \frac{1}{\sigma} &&+ 3.4115 \frac{1}{L} \\
&+ 23.744\, LH &&- 10.898 (LH)^2 &&- 3.5394 \frac{1}{E} &&+ 0.01990 \frac{1}{HG\phi} \\
&+ 20.7470 \frac{1}{\rho_G} &&+ 0.01957 \frac{G V_S^2}{(V_L^2-V_S^2)} &&- 4.4764 \frac{H}{K} &&+ 3.9760 \frac{1}{F} \\
&+ 35.491 (GH)^2
\end{aligned}
$$

Table IV

Standard Deviation of Strength Data

From Several Specific Fits to it

Simple average	S	=	0.45251 Kb
	σ	=	0.2921
Simple fit			(2 terms)
	σ	=	0.2159
Best fit			(33 terms)
	σ	=	0.1970



ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES
OBSERVED ROCK STRENGTH
2.5000+00
2.2500+00
2.0000+00
1.7500+00
1.5000+00
1.2500+00
1.0000+00
7.5000-01
5.0000-01
2.5000-01
0.0000
0.0000
2.5000-01
5.0000-01
7.5000-01
1.0000+00
1.2500+00
1.5000+00
1.7500+00
2.0000+00
2.2500+00
2.5000+00
SIMPLE FIT OF ALL DATA

Figure 8.

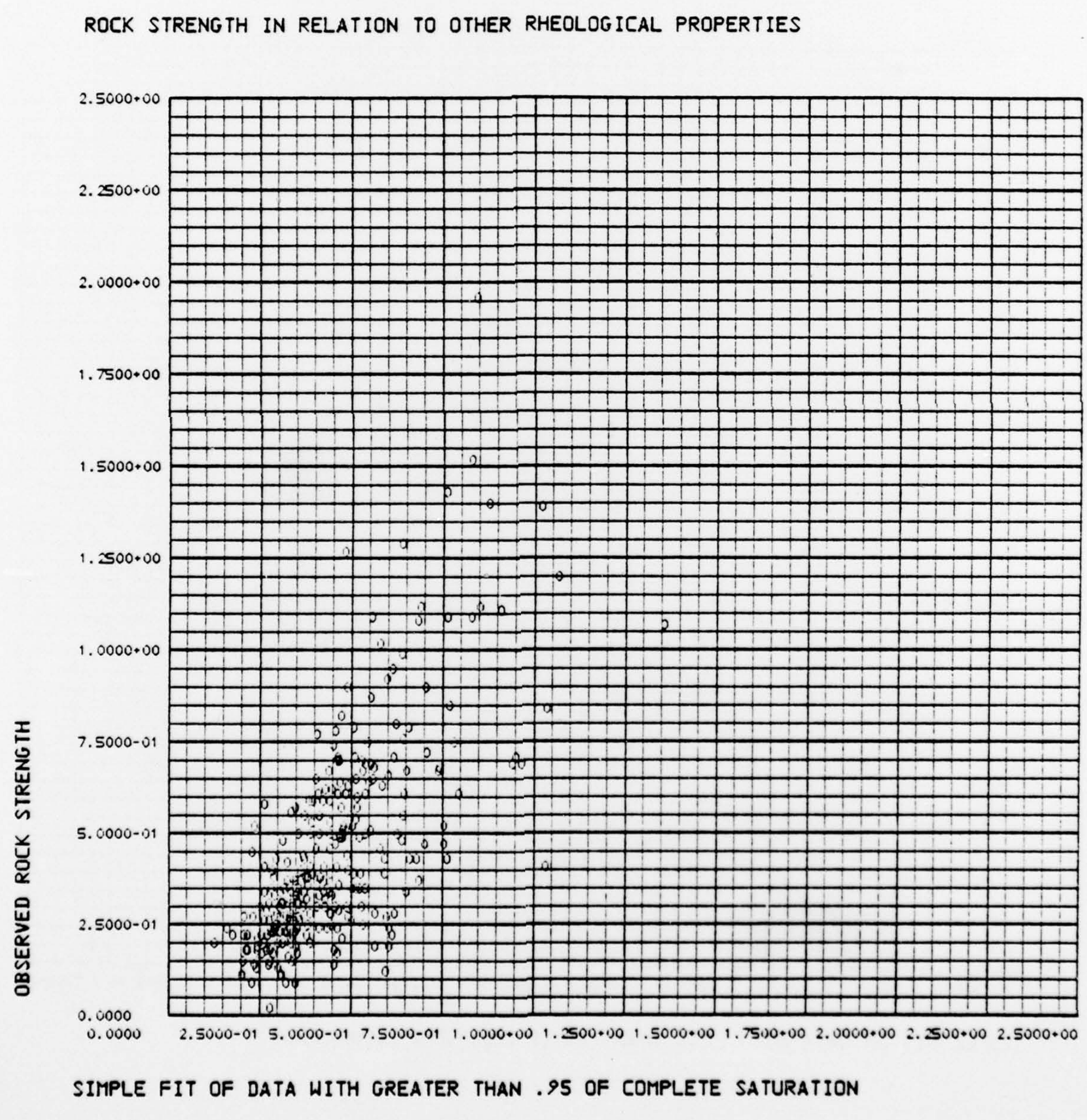
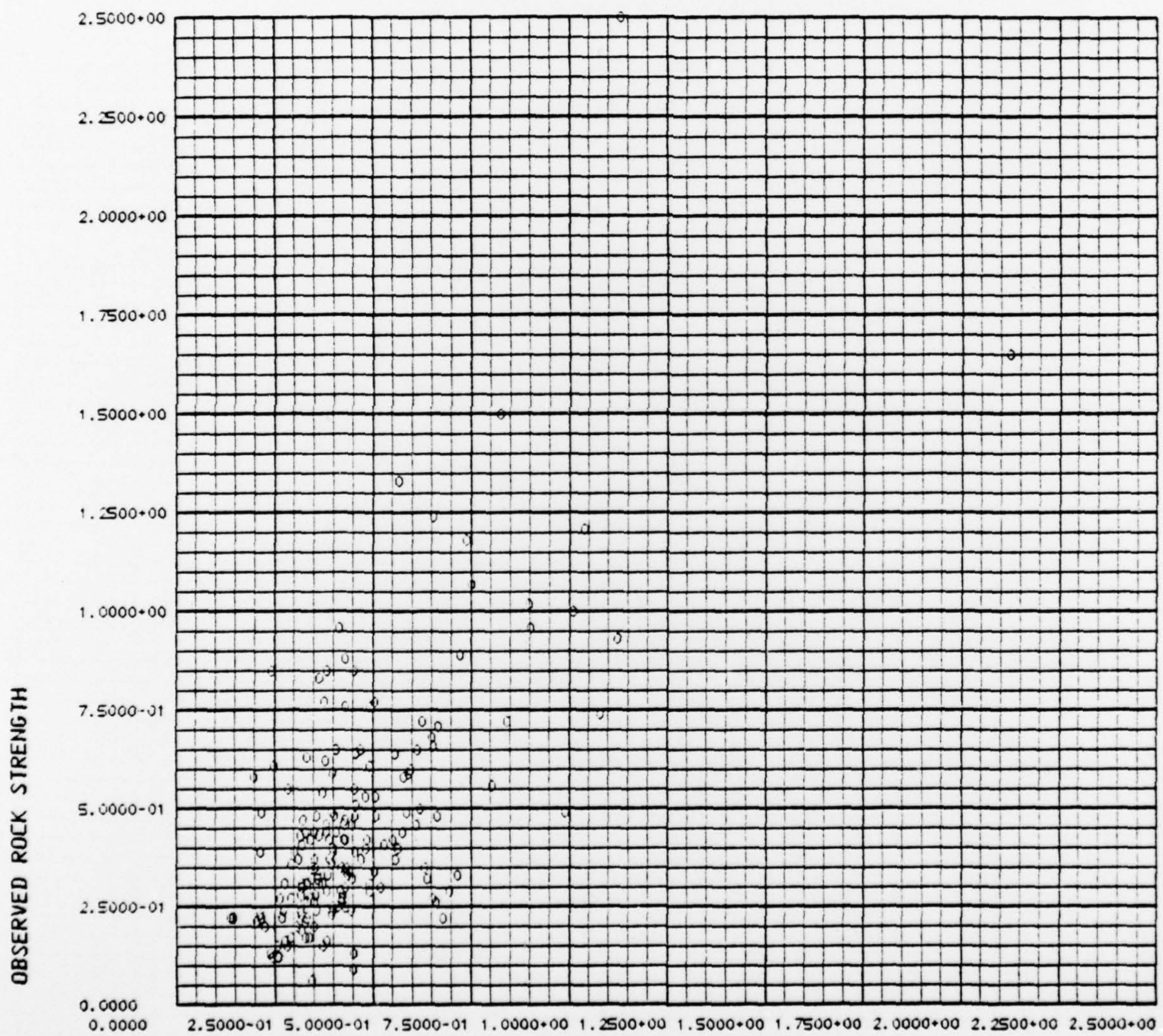

ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES
2.5000+00
2.2500+00
2.0000+00
1.7500+00
1.5000+00
1.2500+00
1.0000+00
7.5000-01
5.0000-01
2.5000-01
0.0000
OBSERVED ROCK STRENGTH
0.0000
2.5000-01
5.0000-01
7.5000-01
1.0000+00
1.2500+00
1.5000+00
1.7500+00
2.0000+00
2.2500+00
2.5000+00
SIMPLE FIT OF DATA WITH GREATER THAN .95 OF COMPLETE SATURATION

Figure 9.

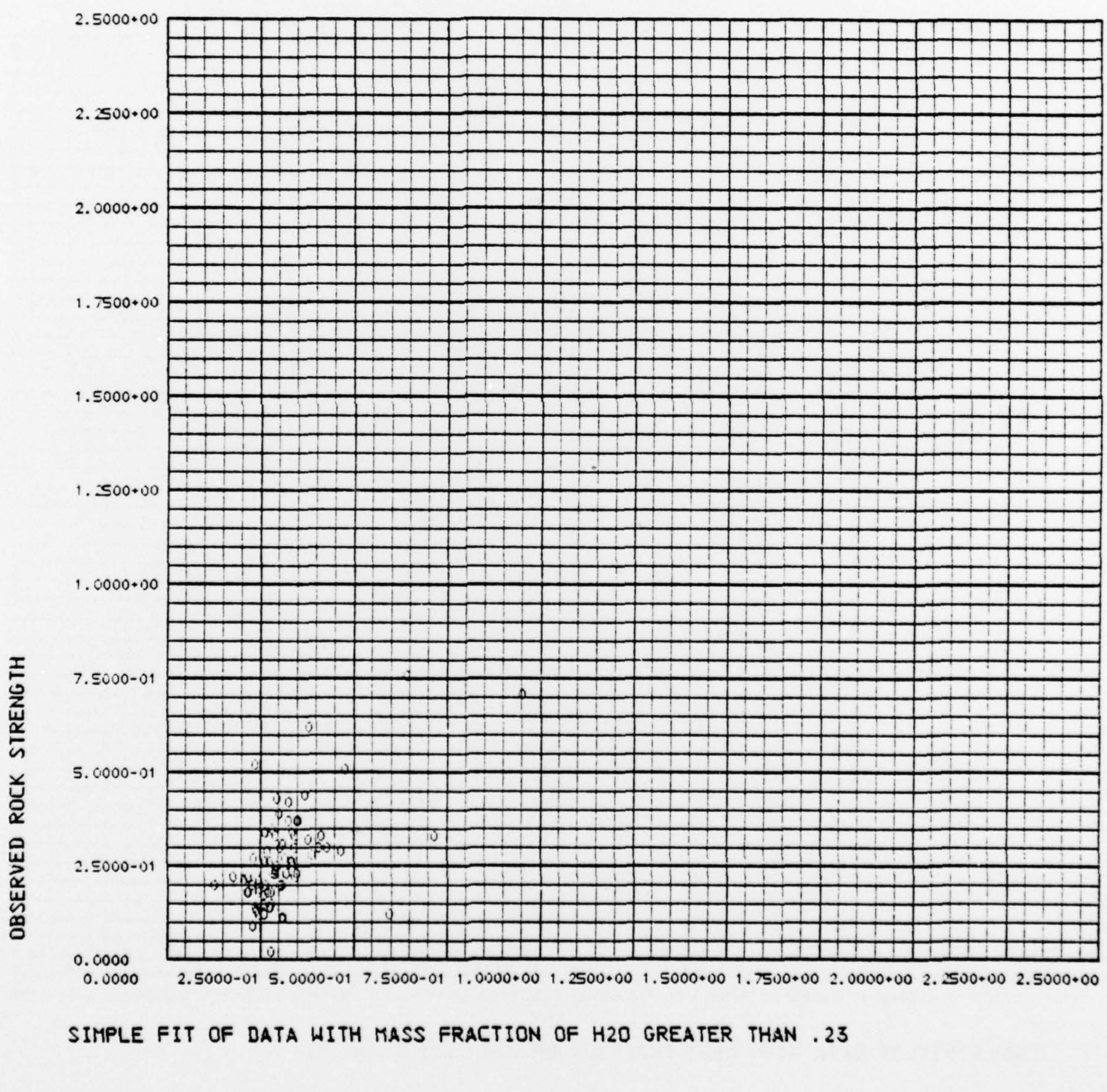
ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES



SIMPLE FIT OF DATA WITH LESS THAN .95 OF COMPLETE SATURATION

Figure 10.

ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES



SIMPLE FIT OF DATA WITH MASS FRACTION OF H2O GREATER THAN .23

Figure 11.

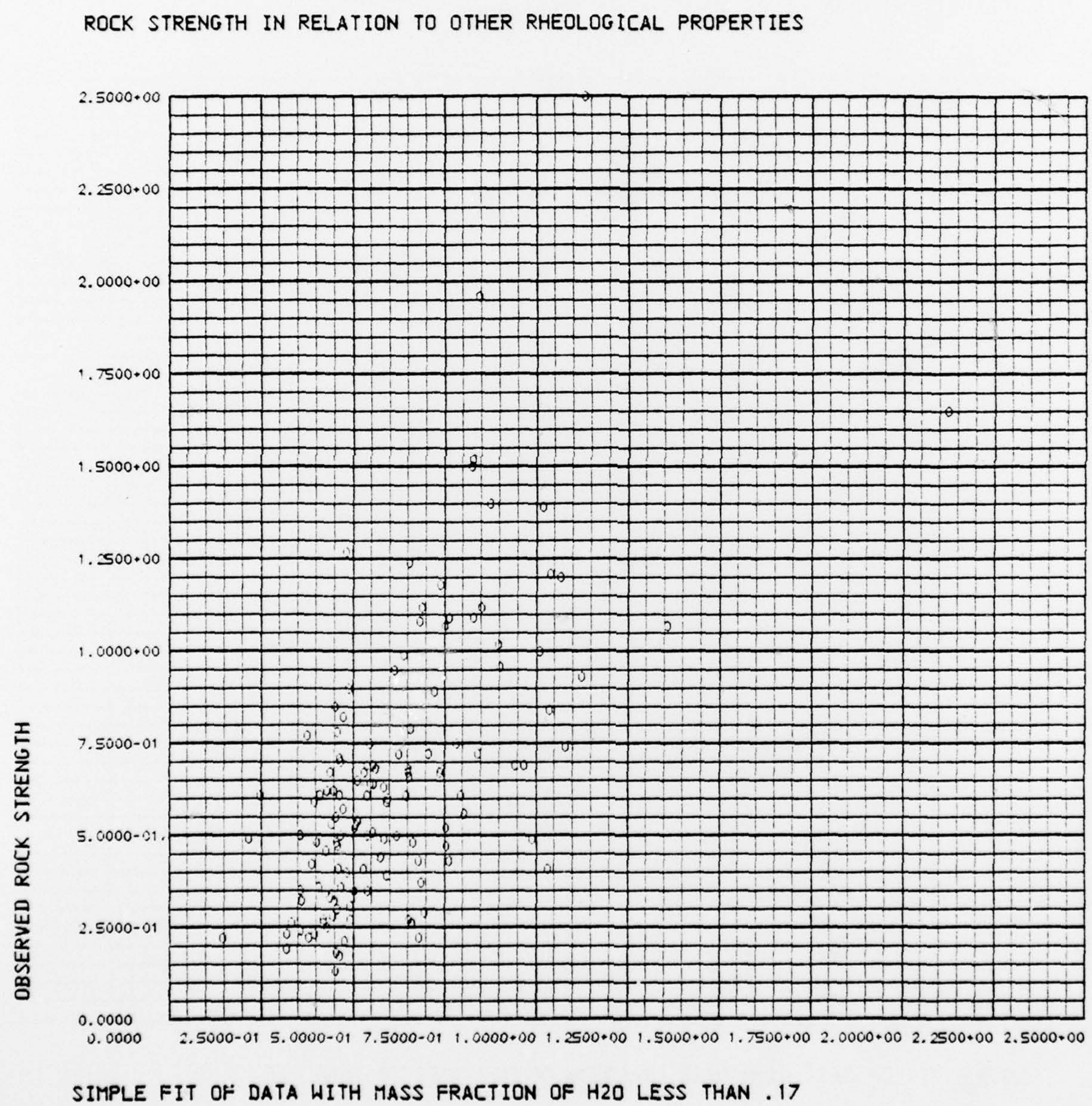
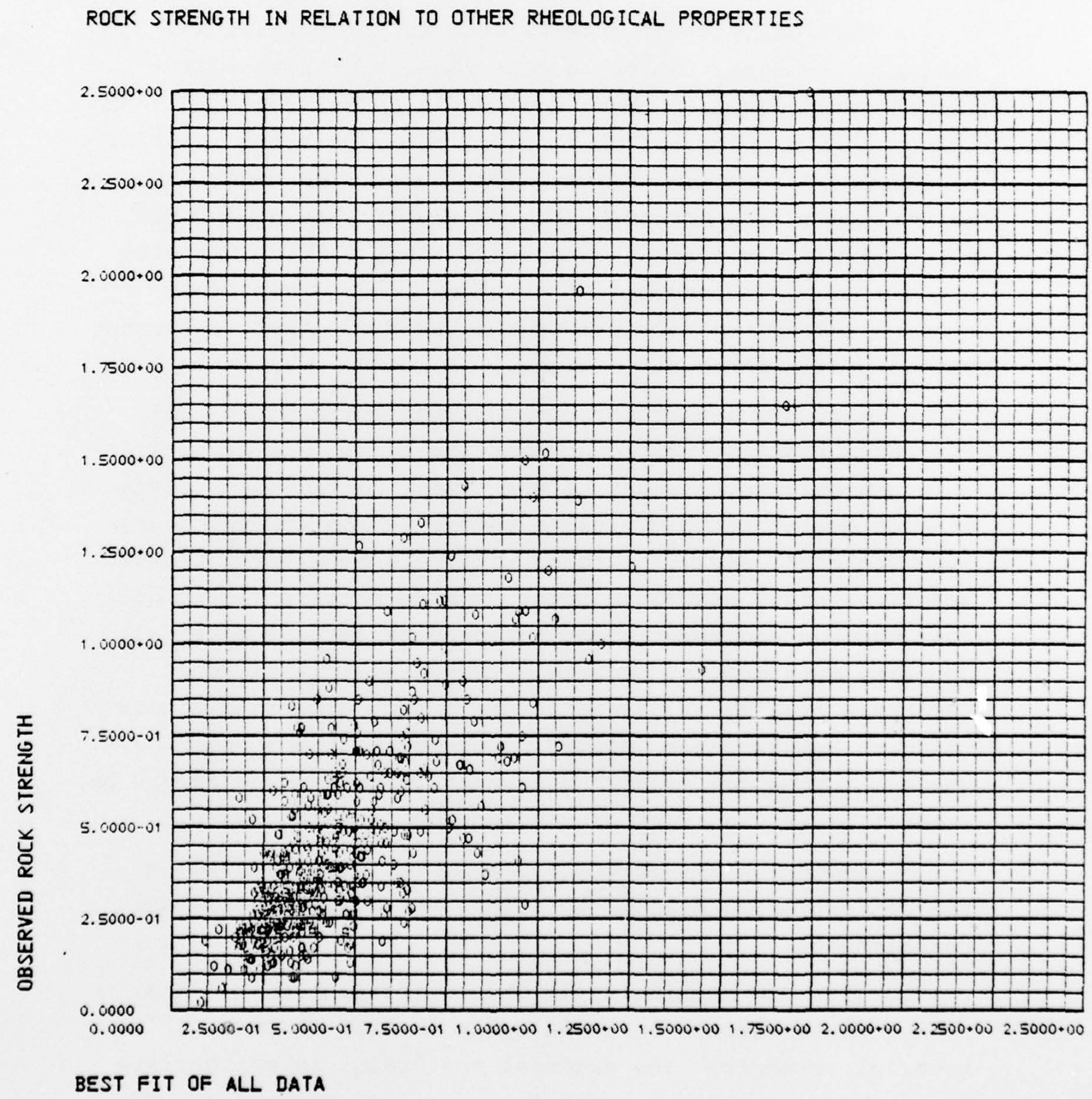

ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES
OBSERVED ROCK STRENGTH
2.5000+00
2.2500+00
2.0000+00
1.7500+00
1.5000+00
1.2500+00
1.0000+00
7.5000-01
5.0000-01
2.5000-01
0.0000
0.0000
2.5000-01
5.0000-01
7.5000-01
1.0000+00
1.2500+00
1.5000+00
1.7500+00
2.0000+00
2.2500+00
2.5000+00
SIMPLE FIT OF DATA WITH MASS FRACTION OF H2O LESS THAN .17

Figure 12.


ROCK STRENGTH IN RELATION TO OTHER RHEOLOGICAL PROPERTIES
OBSERVED ROCK STRENGTH
BEST FIT OF ALL DATA
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2.2500+00
2.0000+00
1.7500+00
1.5000+00
1.2500+00
1.0000+00
7.5000-01
5.0000-01
2.5000-01
0.0000
0.0000
2.5000-01
5.0000-01
7.5000-01
1.0000+00
1.2500+00
1.5000+00
1.7500+00
2.0000+00
2.2500+00
2.5000+00

Figure 13.

3. CONCLUSIONS

This analysis of area 12 material properties and measured strengths indicates that the strength as represented by stress difference at 4 Kb in uniaxial strain tests is not strongly correlated with any other measured material property. In particular, the correlation with water content is weak. One can conclude from this work that if strength values are desired for some purpose, they must be measured or deduced by an independent technique. They cannot be estimated reliably for tuff on the basis of other, conventionally-determined properties.

A strong caveat is certainly appropriate. We all recognize that the statement that the dependence of material strength on water content is weak must be viewed in context. Without question, if one had a tuff in which the water content exceeded, say, 50 percent, it would be a very strange material indeed and would probably have no strength at all. Four hundred and seventy-one independent sets of material property data on real materials were used in this study. For those real materials an effort was made to find a good relation between this definition of strength and other parameters. None was found. That much is true. One should be careful in drawing further conclusions from this work.

Another class of questions should be addressed in the context of material properties, residual stresses and containment.

(1) How meaningful is stress difference at 4 kbar from uniaxial strain tests as a fundamental measure of material strength? The uniaxial constraint is appropriate for a shock process, but not for unloading phenomena. The 4 kbar value is of interest near the shot point, but residual stresses involve stress states closer to 1.0 kbar.

Hopefully an answer to this basic question will be found in the future.

(2) Assuming this stress difference is the value of interest, is it reliably measured? This question involves aspects of intrinsic in-situ material variability and experimental technique. The question is asked because a monumental effort on Mighty Epic apparently led us to a wrong qualitative and quantitative understanding of the strength of that material. Again, this question deserves our attention.

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